Waste Management 74 (2018) 312–322

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

The decay of engineered wood products and paper excavated from landfills in Australia

Fabiano A. Ximenes [a,*], Annette L. Cowie [b], Morton A. Barlaz [c]

[a] Forest Science Unit, NSW Department of Primary Industries, Level 12, 10 Valentine Ave, Parramatta NSW 2150, Australia
[b] NSW Department of Primary Industries, Beef Industry Centre, Trevenna Rd, University of New England, Armidale, NSW 2351, Australia
[c] Dept. of Civil, Construction, & Environmental Eng, North Carolina State University, Box 7908, Raleigh, NC 27695-7908, USA

ARTICLE INFO

Article history:
Received 21 May 2017
Revised 27 October 2017
Accepted 21 November 2017
Available online 2 December 2017

Keywords:
Landfill
Paper
Engineered wood products
Carbon
Decay

ABSTRACT

Large volumes of engineered wood products (EWPs) and paper are routinely placed in landfills in Australia, where they are assumed to decay. However, the extent of decay for EWPs is not well-known. This study reports carbon loss from EWPs and paper buried in landfills in Sydney, Brisbane and Cairns in Australia, located in temperate, subtropical and tropical climates, respectively. The influence of pulp type (mechanical and chemical) and landfill type (municipal solid waste – MSW and construction and demolition – C&D) on decay levels were investigated. Carbon loss for EWPs ranged from 0.6 to 9.0%; though there is some uncertainty in these values due to limitations associated with sourcing appropriate controls. Carbon loss for paper products ranged from 0 to 58.9%. Papers produced from predominantly mechanical pulps generally had lower levels of decay than those produced via chemical or partly chemical processes. Typically, decay levels for paper products were highest for the tropical Cairns landfill, suggesting that climate may be a significant factor to be considered when estimating emissions from paper in landfills. For EWPs, regardless of the landfill type and climate, carbon losses were low, confirming results from previous laboratory studies. Lower carbon losses were observed for EWP and paper excavated from the Sydney C&D landfill, compared with the Sydney MSW landfill, confirming the hypothesis that conditions in C&D landfills are less favourable for decay. These results have implications for greenhouse gas inventory estimations, as carbon losses for EWPs were lower than the commonly assumed values of 23% (US EPA) and 50% (Intergovernmental Panel on Climate Change). For paper types, we suggest that separate decay factors should be used for papers dominated by mechanical pulp and those produced from mostly chemical pulps, and also for papers buried in tropical or more temperate climates.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Large volumes of engineered wood products (EWPs) and paper are consumed in Australia. For 2014–15, 2.0 million tonnes (Mt) of EWPs and 3.6 Mt of paper were consumed, with particleboard and medium-density fibreboard (MDF) accounting for approximately 80% of the total weight of EWPs and printing, writing and packaging papers accounting for approximately 80% of the total weight of paper consumed (ABARES, 2016). Although national estimates of disposal of EWPs in landfills in Australia are not available, an analysis for the State of Victoria suggested that it is substantial, with EWPs accounting for approximately 32% of the total volume of wood waste sent to landfill (Sustainability Victoria, 2014). Although a high proportion of paper is typically recycled in Australia, a significant volume of paper is nonetheless disposed of in landfills: the Federal Department of Environment in Australia estimates that approximately 1.5 Mt of paper is disposed of annually (Department of Environment, 2014). Whereas EWPs are primarily disposed of in construction and demolition (C&D) landfills, significant volumes of paper are found in commercial and industrial (C&I) and in municipal solid waste (MSW) (Department of the Environment, Water, Heritage and the Arts, 2010).

Despite the large quantities of EWPs and paper disposed of in landfills annually, relatively limited research has been conducted on the decomposition of these products under the anaerobic conditions that prevail in landfills. As anaerobic decay of organic materials in landfills results in the generation of carbon dioxide and methane (IPCC, 2006), improved knowledge on the decay of specific components that make up a significant proportion of the

* Corresponding author.
E-mail address: fabiano.ximenes@dpi.nsw.gov.au (F.A. Ximenes).

https://doi.org/10.1016/j.wasman.2017.11.035
0956-053X/© 2017 Elsevier Ltd. All rights reserved.

organic waste stream improves understanding of methane potential and greenhouse gas emissions from waste management.

EWPs are made up primarily of wood particles or fibres bound together with added resins into products that serve a variety of purposes, including structural applications and furniture. Resins typically account for 6–9% of the dry weight of particleboard and approximately 12% for MDF, with wax content ranging from 0.3 to 1% of the total weight (Stark et al., 2010; Xing et al., 2006).

The pulps used in the manufacture of papers can be grouped into two distinct main classes, based on the method of production: mechanical or chemical pulping. In mechanical pulping, the objective is to maintain the majority of the lignin to achieve high yield with acceptable strength and brightness, for use in applications such as newsprint, low-cost books (paperbacks) and telephone directories (Bajpai, 2012). In chemical pulping, which is used for most commercially-produced papers (FAO, 2011), the objective is to remove non-cellulose wood components. A large proportion of the hemicelluloses (30–70%) is degraded and dissolved during chemical pulping (Sjöström and Westermark, 1999). Chemically produced papers contain a considerable proportion of inorganic constituents (primarily calcium carbonate and clay) – up to 30% in copy papers (Kipphan, 2001). These inorganics are added to enhance printing quality and smoothness. Typically, high-quality magazines, catalogues and some types of cardboard contain a high proportion of chemical pulps. The differences in pulp type are likely to influence paper decay rates in landfills, as lignin is considered recalcitrant under anaerobic conditions in landfills (Colberg, 1988; Ham et al., 1993), with recent studies showing no depolymerisation of lignin from a number of substrates including wood and newsprint following anaerobic decay (De la Cruz et al., 2014).

Micales and Skog (1997) postulated that a maximum of 30% of carbon may be lost from paper in landfills, based on published estimates of methane yields. There have been numerous anecdotal reports of paper excavated from landfills after a period of burial (e.g. Kinman et al., 1990; Bogner, 1990; Rathje and Murphy, 1992, Walsh and LaFleur, 1995, Ximenes et al., 2008, Wang et al., 2013). One study (Ximenes et al., 2008) reported retrieving large volumes of a range of paper types after 19–29 years of burial at one landfill in Australia. Decay has only been quantified in a few studies. For example Baldwin et al. (1998) quantified decay from newspapers that had been buried in landfills for up to six years, finding maximum decay of 17.4%. Wang et al. (2013) buried newsprint, copy paper, corrugated containers and a range of EWPs for between 1.5 and 2.5 years in landfills with leachate recirculation, and quantified carbon loss by chemical analysis of the retrieved samples. The carbon losses for EWPs such as particleboard and MDF were minimal, whereas high carbon losses were reported for paper types such as newsprint and corrugated cardboard (47–75%). Other studies have quantified decay of shredded EWPs (Wang et al., 2011) and shredded paper (e.g. Eleazer et al., 1997, Wang et al., 2015) that were exposed to anaerobic conditions in controlled bioreactor experiments. Such quantitative field and laboratory studies have not been carried out for EWPs and paper disposed of in Australian landfills. Furthermore, previous field studies have typically targeted MSW landfills, where conditions are considered more suitable for decay than in C&D landfills, due to a lack of easily decomposed substrates in C&D landfills.

The objective of this study was to determine carbon loss from EWPs and paper buried for varying periods of time in landfills located in contrasting environments in Australia, to better understand the greenhouse gas implications of burying a variety of wood and paper products in landfills. Two hypotheses were tested: (1) papers composed primarily of mechanically produced pulps decay to a lesser extent under anaerobic conditions in landfills than papers derived primarily from chemical pulps, and (2) decay levels for the various products is lower in C&D landfills compared to MSW landfills under similar climatic conditions.

This study focussed on chemical and physical analyses of EWPs and paper excavated from one MSW landfill and one C&D landfill in Sydney, New South Wales, and from two MSW landfills, located in Brisbane and Cairns, Queensland, Australia.

2. Materials and methods

2.1. Sites description

Two of the landfills were located in Sydney, New South Wales, and two in Queensland, (Brisbane and Cairns), where the temperature and rainfall are higher (Table 1).

In Table 2 we describe key characteristics of each of the landfills excavated. Although the exact composition of the waste in the landfills excavated was not measured, they received waste typical of MSW and C&D landfills in their regions. Time since closure was determined in consultation with landfill operators and also by the dates in excavated newspapers, magazines and telephone books.

The pH and temperature of the waste at different depths was recorded at the Sydney and Brisbane sites but not in Cairns due to instrument failure.

2.2. Physical and chemical analyses

2.2.1. Sample identification and moisture content

A total of 295 samples of EWPs and 354 paper samples were excavated from the four landfills (Tables 3 and 4). The EWPs and paper samples excavated represented a wide range of sizes, for example from small EWP offcuts to large particleboard panels. All samples were labelled, identified to type and sealed in plastic bags prior to storage at 4 °C.

Moisture content was determined on samples from a random subset of the excavated EWP and paper samples by oven-drying at 103 ± 2 °C until constant weight (AS/NZS 1080.1, 1997). The moisture content of the samples was expressed as mass water/mass wet weight (percentage).

2.2.2. Chemical analysis

A total of 130 EWPs and 175 paper samples were randomly selected for chemical analyses, by using the "random" function in Microsoft Excel, applied to each category of EWP and paper products. Where the number of samples recovered allowed, the minimum number of samples randomly selected for each product category was three. Sourcing of matching controls for chemical analyses of EWPs was challenging. A sample of plywood (provided by the Engineered Wood Products Association of Australia) produced around the same time the plywood samples excavated from the landfills would have been discarded (16–20 years prior to the excavation date) was used as a control. Samples of particleboard manufactured approximately 11 and 17 years prior to the excavation dates were obtained and used as controls. As it was not possible to source a MDF control sample that matched the burial times, a MDF sample produced at the time of the excavation was used as a control. For paper, the publication details in the samples made it possible to source closely-matched controls for many samples. This provided a unique opportunity to quantify potential carbon loss from the landfill samples by comparing the chemical composition of the excavated samples to that of controls. The same level of rigor could not be applied to samples that were difficult to match with pre-existing controls, such as more obscure publications and paper types such as cardboard.

Prior to chemical analysis, the landfill and control samples were oven-dried at 40 °C for four days (as samples with excessive

Table 1
Mean annual temperatures and rainfall for Cairns, Brisbane and western Sydney. Source: Bureau of Meteorology, 2014

Location	Mean annual maximum temperature (°C)[a]	Mean annual minimum temperature (°C)[b]	Mean annual rainfall (mm)	Latitude
Cairns	29.0	20.8	2011	16.9186°S, 145.7781°E
Brisbane	25.5	15.7	1149	27.4698°S, 153.0251°E
Sydney	24.3	12.7	872	33.8688°S, 151.2093°E

[a] The average daily maximum air temperature calculated for all years of record.
[b] The long-term average daily minimum air temperature observed during a calendar month and over the year.

Table 2
Key characteristics of the landfill sites excavated.

Landfill location	Landfill type	Time since closure (years)	Capping layer[a]	Maximum height of landfill (m)	Timing of excavation	Comments
Brisbane (Roghan Road)	MSW	18	Minimal[b]	3.5–6.5	Summer	Electricity generation from recovered methane
Cairns (Portsmith)	MSW	16–18	Minimal	3.5	Summer	Site within a protected mangrove wetland
Sydney (Eastern Creek)	MSW	6, 14, 16 and 18	Clay and loam soil (1.5 m)	8–10	Winter	Electricity generation from recovered methane. Strong ammonia odour from cell with 6-year old waste
Sydney (Brandown)	C&D	19–20	Clay and loam soil (0.5–1.5 m)	7	Winter	Large volumes of bricks, and smaller amounts of concrete and steel were also found

[a] None of the sites had engineered caps to minimise infiltration.
[b] Minimal layer was typically comprised of a thin layer of soil with no specifications as to its hydraulic conductivity.

Table 3
EWP samples excavated and analysed from the four landfills (E = excavated samples; A = analysed samples).

Landfill	Particleboard		MDF		Plywood		Veneer	
	E	A	E	A	E	A	E	A
Sydney (C&D)	44	29	22	19	28	6	22	6
Brisbane (MSW)	21	20	19	19	22	5	5	5
Cairns (MSW)	3	3	9	9	11	8	8	0
Sydney (MSW)	30	0	13	0	15	0	23	0
Total	98	52	63	48	76	19	58	11

Table 4
Paper types excavated and analysed from the four landfills (E = excavated samples; A = analysed samples).

Landfill	NP[a]		PB[a]		MG[a]		TD[a]		CB[a]	
	E	A	E	A	E	A	E	A	E	A
Sydney (C&D)	16	4	5	2	5	4	1	1	12	8
Brisbane (MSW)	65	31	0	0	13	10	1	1	12	8
Cairns (MSW)	27	12	1	1	17	10	6	3	10	8
Sydney (MSW)	47	47	17	10	30	8	5	5	29	0[b]
Total	155	94	23	13	65	32	13	10	63	24

[a] NP = newsprint; PB = paperbacks; MG = magazines; TD = telephone directories; CB = cardboard.
[b] For the Sydney (MSW) samples, preference for analysis was given to samples for which matching controls could be found, thus cardboard samples were not included.

moisture hinder the milling process), and milled using a Retsch mill to pass a 1.0 mm screen. This material was sampled from the same paper types used for the moisture content determinations described in 2.2.1. Sub-samples from the extremities and centre of the EWP samples were ground and composited prior to analyses. For selected paper samples (newspapers, magazines, paperbacks and telephone directories), where possible (i.e. where all pages were present) pages were extracted from the beginning, middle and end portion of each paper sample (with greater representation from "middle" samples as that represented the bulk of the sample), ground and composited prior to analyses.

All EWP and paper samples analysed were treated sequentially with dichloromethane, acetone and methanol to eliminate naturally occurring extractives as described in Ximenes et al. (2015).

The chemical analyses carried out here were described in detail in Ximenes et al. (2015). The approach for paper samples from Sydney MSW landfill differed from that applied to samples from the other landfills. The main difference was that the holocellulose portion (cellulose and hemicellulose portions combined) was not directly determined but rather derived as the difference between the total mass of the sample and the other measured components (sum of acid soluble lignin, acid insoluble lignin, organic extractives and ash). This approach was followed because at the time of the determinations, confidence in the results obtained from the enzymatic neutral detergent fibre (ENDF) and acid detergent fibre (ADF) determinations conducted for excavated paper samples was low.

Acid-insoluble lignin was determined by the traditional Klason method (AOAC, 1995), whereas the acid-soluble lignin was determined using the conventional UV spectrophotometric method (absorption at 205 nm). Ash content was determined by recording weight loss after combustion for 4 h at 575 °C (NREL, 2008).

In the period between the Sydney MSW landfill excavation and the other excavations, capability was developed to conduct ENDF and ADF tests, enabling direct determination of the holocellulose. The holocellulose component was calculated as the difference between the ENDF and the Klason lignin. The control samples for all landfills were analysed by the same methods as applied to the matched landfill samples. The holocellulose and lignin values were normalised to the organic solids to exclude the impact of the presence of additional, non-naturally occurring inorganic compounds that may have been absorbed by the samples in the landfill (e.g., soil). The normalised holocellulose and lignin components were used for the calculation of carbon loss for all landfill samples.

2.2.3. Carbon loss determinations

Carbon loss was calculated assuming that lignin (acid-insoluble + acid-soluble) is recalcitrant under anaerobic conditions (Colberg, 1988, Ham et al., 1993). Thus, if the mean concentration of lignin for sub-samples from a EWP or paper sample from landfill was greater than the mean concentration of lignin for the equivalent controls, as would be the case if some cellulose and hemicellulose were decomposed, then the associated carbon loss was determined as described by Eqs. (1)–(3) below (based on Hedges et al., 1985) – these steps are described in detail in Ximenes et al. (2015). First, the factor by which the lignin concentration is increased in the landfill samples (Eq. (1)) was calculated. If F is less than 1, this was attributed to the loss of holocellulose which was quantified by Eq. (2) in which P represents the fraction of the holocellulose that was not decomposed. If F equals "1", then it is assumed that the holocellulose remains intact. Finally, the carbon loss in the landfill samples was determined as the loss of carbon in the holocellulose fraction of the landfill sample compared with the total mass of carbon in the control sample (Eq. (3)).

$$F = \text{lignin } \% \text{ (control)} / \text{lignin } \% \text{ (landfill)}. \quad (1)$$

$$P = [\text{holocellulose } \% \text{ (landfill)} / \text{holocellulose } \% \text{ (control)}] \times F. \quad (2)$$

$$\text{C loss } (\%) = [\text{holocellulose } \% \text{ (control)} \times \text{carbon fraction in holocellulose} \times (1 - P)] / \text{carbon fraction of the control sample} \quad (3)$$

The total mass of carbon in the control sample was calculated assuming that the carbon concentrations of cellulose and hemicellulose were 44.4% (based on the molecular weight of carbon in the cellulose unit) and 45% (based on the molecular weight of carbon in pentosan and hexosan units), respectively, and the average (44.7%) was used as the carbon concentration of holocellulose. The carbon concentration of lignin was assumed to be 63% for softwoods and 58% for hardwoods (Fengel and Wegener, 1984). Deriving the mass of carbon by directly measuring the carbon concentration of the samples instead would have resulted in misleading values. This is because in the case of significant decay of the carbohydrates and no loss of lignin (the likely scenario), the carbon concentration of the decayed sample, if directly measured, would have increased due to the fact that lignin, which is enriched in the decomposed sample, has a higher carbon concentration than carbohydrates.

3. Results and discussion

3.1. Temperature and pH of waste

The temperature and pH of the waste varied over a narrow range for the Sydney C&D and Brisbane MSW landfills. The temperature ranged from 25 to 28 °C and 24–24.5 °C for the cells at Sydney C&D, and the pH ranged from 6.6 to 7.4. For Brisbane MSW, the temperatures typically ranged from 24 to 27 °C and the pH ranged from 6.4 to 7.8. For Sydney MSW, the temperature of the "newest" waste (6-year old) was significantly higher ($p < 0.05$) than for waste buried for longer periods (Table 5). The pH of the waste decreased gradually with an increase in the period of burial (Table 5). The temperature of waste excavated from deeper in the cells (5–10 m) was invariably higher than for waste closer to the surface (Table 5). The higher pH for the "newest" waste correlated with the higher temperatures for that cell (Table 5).

3.2. Visual appearance and moisture content of EWPs and paper excavated from landfills

The majority of the EWP excavated showed no obvious visual signs of decay (Fig. 1a and b). Newspapers, although wet, were mostly intact, whereas other paper types such as magazines appeared to have higher levels of deterioration (Fig. 1c and d). It is important to note that newsprint can be legible and still exhibit carbohydrate loss; thus quantitative chemical analysis of the papers is critical. Typically, the excavated papers were heavily stained and at times brittle during handling.

Although the moisture content of individual EWPs and paper samples varied greatly across landfill types and depths, all samples were relatively wet (Fig. 2). The moisture content of 95% of all samples tested were above the moisture content equivalent to the fibre saturation point of wood (30%). This suggests that moisture content was generally not a limiting factor for decay. The moisture content of EWPs and paper excavated from Cairns MSW was higher than for other landfills – most likely due to the higher annual rainfall for Cairns (Table 1), and the fact the landfill was located within a mangrove wetland.

Visually, very little food waste was observed in the cells excavated in MSW landfills, suggesting that the landfills sustained active microbial communities that had decomposed the food waste.

3.3. Lignin and holocellulose concentration and carbon losses for samples excavated from landfills

Changes in the normalised lignin concentration and normalised holocellulose (i.e. extractive and ash-free) were used here to determine carbon loss. The following criteria was used to rate the levels of carbon loss calculated: 0–5% – no to minimal loss; 5–10% – minor loss; 10–20%: low loss; 20–30%: moderate loss; 30–50% – high loss; greater than 50% – severe loss.

These criteria were necessary because, especially in the case of EWPs, the limited number of controls available and at times the limited number of samples retrieved made it difficult to determine the significance of the differences in lignin concentrations, and therefore the significance of the calculated carbon losses. Furthermore, it was possible that the controls used may not have been an

Table 5
Mean temperature and pH of waste from Sydney MSW.

Age of burial (years)	pH (Mean, SD)	Temperature (°C; 0–5 m Mean, SD)	Temperature (°C; 5–10 m Mean, SD)
18	6.4 (0.96)	21.7 (2.4)	26.8 (2.4)
16	6.97 (1.1)	20.0 (5.4)	23.1 (4.3)
14	7.8 (0.78)	22.8 (2.6)	25.0 (2.1)
6	8.6 (0.46)	30.2 (5.8)	36.1 (3.7)

(a) Particleboard samples (Brisbane MSW)

(b) MDF samples (Sydney MSW)

(c) Magazine sample (Brisbane MSW)

(d) Newspaper sample (control on top, landfill sample at the bottom, Sydney MSW)

Fig. 1. Examples of EWPs and paper products excavated from the excavated landfills (a) particleboard (Brisbane MSW), (b) MDF (Sydney MSW), (c) magazine samples and (d) newspaper (control on top, landfill sample at the bottom, Sydney MSW).

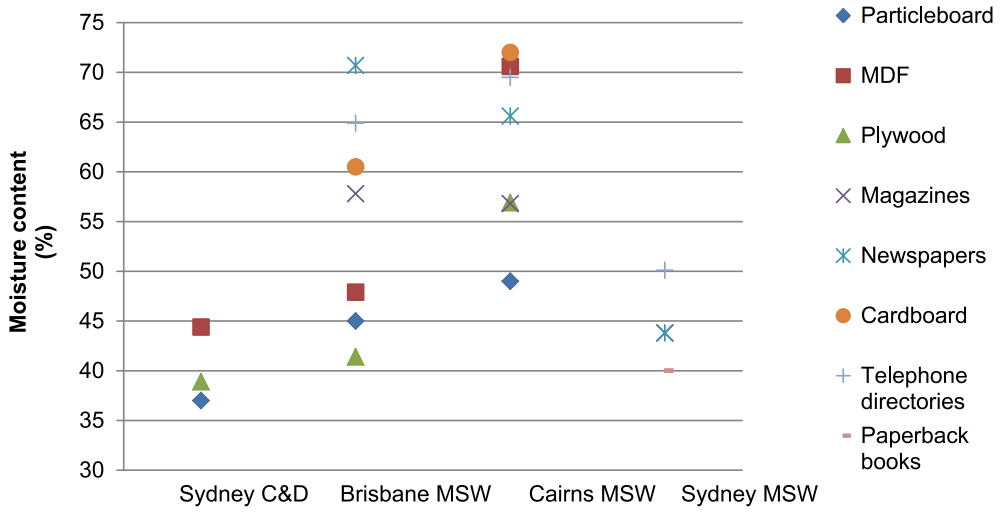

Fig. 2. Average moisture content of EWPs and paper excavated from the four landfills.

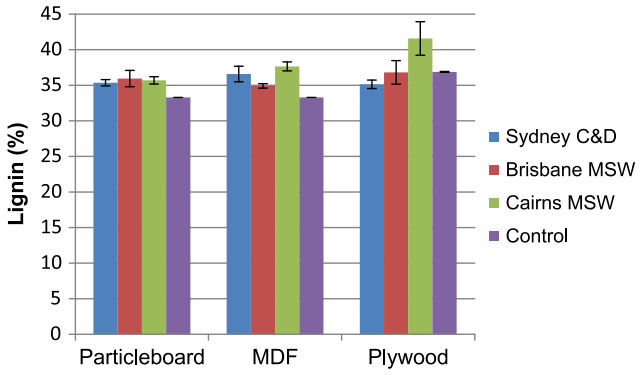

Fig. 3. Total lignin (%; extractive free and ash-free) for EWPs from three landfills and controls (error bars represent the standard error of the mean).

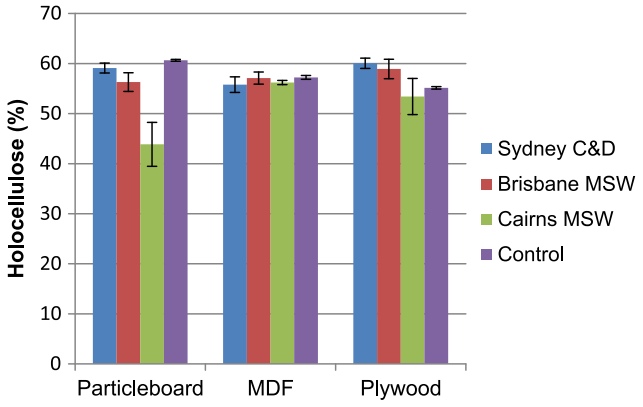

Fig. 4. Holocellulose (%; extractive free and ash-free) for EWPs from three landfills and controls (error bars represent the standard error of the mean).

ideal match to the landfill samples (in terms of wood species and binders used).

3.3.1. Lignin and holocellulose concentration and carbon losses for EWPs excavated from landfills

The lignin concentration (combined acid soluble and acid insoluble lignin) and holocellulose for EWPs and paper excavated from three landfills are presented in Figs. 3 and 4. The lignin concentration of the excavated particleboard and MDF samples was slightly higher than that of the control samples for all landfills (Fig. 3). The holocellulose concentration of particleboard and MDF samples also did not differ much from that of control samples, with the exception of Cairns MSW particleboard samples (Fig. 4). However the number of samples excavated and analysed was low (3) compared to the other landfill sites (Table 3, Methods).

A visual assessment of the colour of the ground control plywood used suggests the plywood sample was made up of hardwood veneers. However, similar observations on the excavated plywood samples from all landfills suggest they were mostly softwoods. Thus results need to be interpreted with a degree of caution, as differences in species composition could account for differences in lignin concentration observed.

The lignin concentration of excavated plywood from Brisbane MSW and Sydney C&D was similar to that of control samples, whereas plywood excavated from Cairns MSW had higher lignin concentration than controls (Fig. 3).

The ash concentration of analysed landfill samples and controls is included in Table 6. Typically the ash concentration of the excavated samples was significantly higher ($p < 0.05$) than that of control samples due to the absorption of inorganics over the duration of burial. The increase in ash may be offset in some cases by a potential reduction in extractive levels due to leaching.

The calculated carbon losses for particleboard were similarly minor for all landfills, ranging from 5.8% for Sydney C&D to 6.6% for Brisbane MSW (Fig. 5). The calculated carbon losses for plywood and veneer were also low, ranging from 0.6% for Sydney C&D to 9.0% for Cairns MSW, though with comparatively large standard errors (Fig. 5). The low carbon losses found here are consistent with results from Wang et al. (2011, 2013). Wang et al. (2013) found insignificant degradation for MDF samples and mild degradation of particleboard samples, while oriented stranded board (OSB) samples exhibited the highest biodegradation (19–50% loss of holocellulose) after burial in landfill for 1.5–2.5 years. Wang et al. (2011) placed EWPs (including particleboard and MDF) in anaerobic bioreactors under controlled conditions. At the completion of their experiment, the carbon loss determined for particleboard and MDF was 1.3 and 1.1%, respectively.

Although similar in range to results from Wang et al. (2011), carbon losses reported here for EWP were generally slightly higher – this is surprising as bioreactor experiments are typically conducted under conditions optimal for anaerobic decay, and therefore, can be assumed to represent the maximum extent of decay theoretically possible in MSW landfills. Possible explanations for the greater level of decay here include some decay prior to disposal (which was not tested), or perhaps an artefact due to the uncertainties associated with the selection of control samples and the inherent variability in the excavated EWPs themselves. The possibility of decay prior to landfill exposure has been discussed in Ximenes et al. (2015). Differences in the type of adhesives and additives used (e.g. wax emulsions, preservatives, fire retardants) and in wood species used in the manufacture of EWPs excavated from landfill and controls may also have contributed to differences in the chemical composition of EWPs. Wang et al. (2011) conducted Klason lignin analysis on phenol formaldehyde used in the manufacture of plywood and demonstrated that it behaved like lignin. However, as plywood typically contains relatively small amounts of resin (around 3%, Wang et al., 2011), the confounding effect is likely small. This is not an issue for particleboard and MDF, as the resin used is based on urea formaldehyde, which does not behave like lignin (Wang et al., 2011). EWPs can include both softwoods and hardwoods in their composition, and non-wood fibre such as agricultural residues may also be used (Stark et al., 2010). Hardwoods typically have higher amounts of acid-soluble lignin than softwoods (Brunow et al., 1999); thus, if as was the case for plywood in our study, the control is likely made of hardwoods

Table 6
Ash concentration (%) for EWP and paper products excavated from four landfills and controls. Standard deviation and number of samples are given in parentheses.

Landfill site	MDF	Particleboard	Plywood/Veneer	Newspaper	Magazine	Telephone directory	Card board	Paper back
Sydney (C&D)	4.1 (3.3, 19)	5.1 (6.7, 28)	3.2 (2.5, 12)	12.9 (13.6, 4)	24.7 (4.1, 3)	6.8 (NA, 1)	8.7 (4.8,6)	NA
Brisbane (MSW)	6.1 (4.5, 18)	9.6 (10.3, 20)	4.1 (1.9, 10)	5.0 (2.9, 31)	32.9 (0.8, 3)	3.8 (NA, 1)	9.8 (5.8, 8)	NA
Cairns (MSW)	4.5 (1.7, 9)	23.6 (17.7–29.6)	5.2 (3.1, 7)	2.5 (1.1, 10)	48.3 (3.5, 7)	4.1 (1.9, 3)	15.6 (1.6, 3)	NA
Sydney (MSW)	NA	NA	NA	4.5 (1.9, 46)	26.3 (12.7, 5)	4.3 (1.3, 5)	NA	7.3 (4.8, 10)
Controls	0.3 (NA, 1)	0.5 (NA, 1)	2.85 (2.8–2.9)	0.6 (0.5, 20)	25.6 (5.3, 9)	5.0 (0.9, 3)	9.1 (4.9,3)	1.2 (1.3,7)

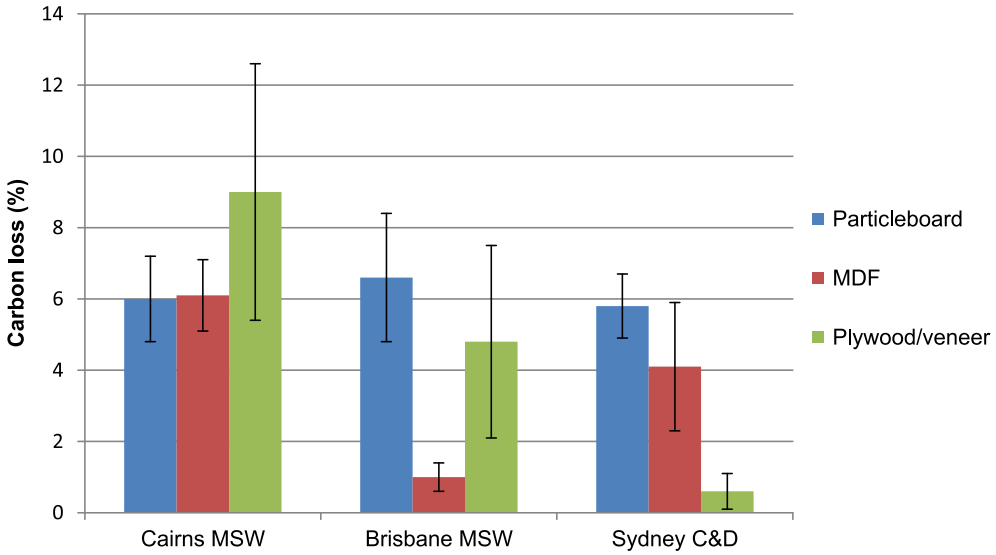

Fig. 5. Carbon loss for EWPs from three landfill sites (error bars represent the standard error of the mean).

Table 7
Lignin (acid-soluble and acid insoluble portions combined) and holocellulose concentration (%) for newspapers excavated from four landfills and controls. Standard deviation and sample number are given in parentheses.

Landfills	Lignin		Holocellulose	
	Sample Concentration (SD, N)	Control Concentration (SD, N)	Sample Concentration (SD, N)	Control Concentration (SD, N)
Sydney MSW (18 years)	27.1 (3.2, 26)	29.1 (0.5, 3)	64.8 (3.4, 26)	68.6 (0.7, 3)
Sydney C&D (19–20 years)	23.7 (6.5, 4)	24.8 (0.8, 3)	64.4 (10.6, 4)	72.7 (1.1, 3)
Brisbane MSW (18 years)	29.2 (4.0, 31)	26.9 (1.7, 8)	64.7 (6.5, 31)	70.2 (1.7, 8)
Cairns MSW (16–18 years)	31.4 (2.7, 10)	26.2 (1.7, 2)	64.5 (3.7, 10)	70.3 (1.5, 2)
Sydney MSW (14–16 years)	28.8 (3.9, 13)	26.0 (2.0, 6)	61.1 (3.9, 13)	71.5 (1.6, 6)
Sydney MSW (6 years)	31.8 (2.5, 7)	25.4 (NA, 1)	57.8 (4.4, 7)	68.3 (NA, 1)

whereas excavated samples are comprised of softwoods, the carbon losses may be underestimated.

3.3.2. Lignin and holocellulose concentration and carbon losses for paper excavated from landfills

Paper products are commonly discarded while they have complete physical integrity, because, unlike wood products, their service life is unrelated to their physical condition. They also typically have much shorter service lives than wood products (IPCC, 2014). This means that any decay determined for paper excavated from landfills can be typically attributed to microbial activity in the landfill rather than occurring prior to disposal. Furthermore, the matching controls for many paper types (e.g. newspapers, magazines, telephone directories and paperback books) increases the confidence in the carbon loss estimation for those products.

The lignin concentration (combined acid soluble and acid insoluble lignin) and holocellulose for newspaper samples excavated from six different locations in four landfills is presented in Table 7. Newspapers were the most abundant paper type, and also the easiest paper type for which to find matching controls. The mean lignin concentration of excavated newspapers was higher than for the control samples for four of the six landfill sites excavated, and the holocellulose concentration was lower than for controls for all sites (Table 7).

The lignin concentration of paper types other than newspapers excavated from Cairns MSW was the highest compared to similar paper types in other landfills (Table 8). Interestingly the differences in lignin concentration between one of the magazines excavated from Sydney MSW (“New Idea”, a popular title printed on uncoated mechanical pulp) and its control were similar to those determined for two other New Idea magazines excavated from Cairns MSW (results not shown). The variability in the lignin concentration in magazines from Sydney MSW was high (Table 8).

The only landfill for which the chemical composition of excavated paperback books was determined was Sydney MSW. Paperback books are generally printed on what is termed ‘bulky news’, on 100% uncoated mechanical pulp. Apart from two of the paperback books analysed, which had been buried for 6 years, the remainder had been buried for 14–18 years.

The holocellulose concentration of the landfill paper was lower than that of control samples, with the exception of telephone directories from Sydney C&D and Sydney MSW – though the number of landfill samples tested was low (Table 8).

The ash content of the magazine samples was on average the highest of all paper types, ranging from 26.3 to 48.3% (Table 6), due to the high amounts of additives. The ash concentration of the landfill paperback books was significantly higher than for the control samples (Table 6).

Carbon losses for paper from Cairns MSW were higher than for other landfills (Fig. 6). Carbon losses for newspapers ranged from 6 to 14.8% (Fig. 6). Carbon losses for newspapers from Sydney MSW (14–16 years) and Sydney MSW (6 years) were similar, matching the visual assessment of decay for those samples (typically mild); however newspapers recovered from Sydney MSW (18 years) were also visually assessed as having “mild decay”, and yet they had no carbon loss (Fig. 6). This suggests that visual assessment is not a reliable guide for assessing potential carbon losses. There was no

Table 8
Lignin (acid-soluble and acid insoluble portions combined) and holocellulose concentration (%) from paper types other than newspapers. Standard deviation and sample number are given in parentheses.

Paper type	Landfills	Lignin		Holocellulose	
		Sample concentration (SD, N)	Control concentration (SD, N)	Sample concentration (SD, N)	Control concentration (SD, N)
Magazines	Sydney C&D	14.7 (0.02, 2)	15.2 (NA, 1)	51.2 (3.9, 2)	57.0 (NA, 1)
	Brisbane MSW	18.0 (0.8, 3)	18.4 (2.9, 3)	47.1 (0.2, 3)	68.4 (12.8, 3)
	Sydney MSW	26.6 (8.5, 5)	21.5 (0.6, 5)	42.7 (19.0, 5)	52.5 (5.0, 5)
	Cairns MSW	26.0 (1.3, 7)	15.25 (1.4, 4)	23.0 (4.5, 7)	53.8 (3.5, 4)
Telephone directories	Sydney C&D	18.3 (NA, 1)	20.5 (0.25, 2)	79.9 (NA, 1)	78.4 (0.5, 1)
	Brisbane MSW	22.5 (NA, 1)	20.5 (0.25, 2)	72.7 (NA, 1)	78.4 (0.5, 1)
	Sydney MSW	21.3 (0.6, 4)	29.4 (NA, 1)	71.6 (1.9, 4)	69.0 (NA, 1)
	Cairns MSW	34.1 (3.3, 3)	21.5 (0.4, 3)	59.0 (3.3, 3)	70.7 (0.5, 3)
Cardboard	Sydney C&D	20.6 (8.6, 6)	13.6 (2.0, 2)	65.2 (14.4, 6)	70.5 (4.5, 2)
	Brisbane MSW	17.7 (4.4, 8)	13.6 (2.0, 2)	67.8 (13.0, 8)	70.5 (4.5, 2)
	Cairns MSW	32.3 (2.7, 2)	13.1 (1.7, 3)	43.0 (4.1, 2)	69.4 (3.7, 3)
Paperback books	Sydney MSW	25.3 (7.6, 10)	27.5 (2.2, 7)	65.7 (5.4, 10)	70.3 (2.9, 7)

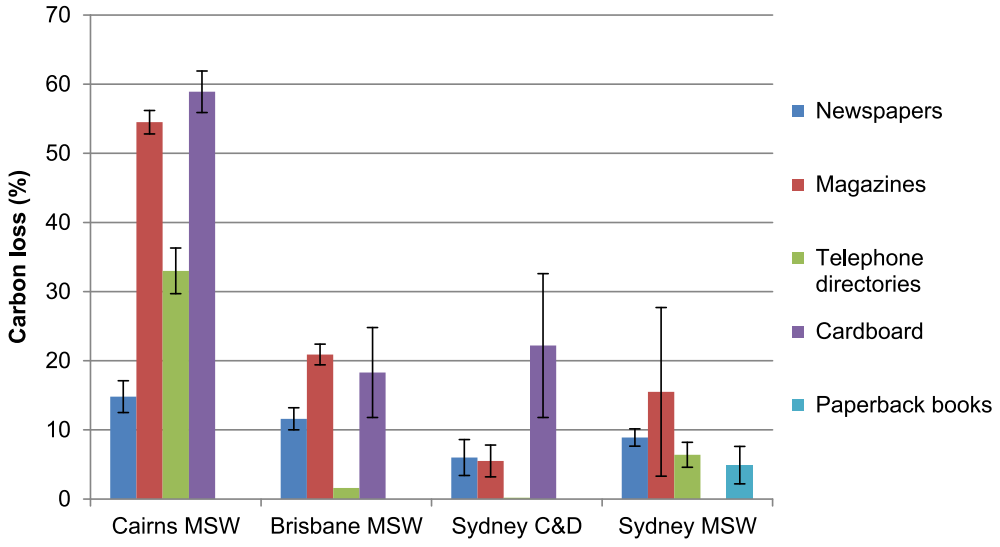

Fig. 6. Carbon loss for paper products from four landfill sites (error bars represent the standard error of the mean).

clear correlation between depth of burial and extent of carbon loss, as exemplified in Fig. 7. The majority of samples were recovered from a depth of 3–6 m, with carbon losses ranging from none/minimal to low (Fig. 7). Newspapers recovered from shallower portions of the Sydney MSW landfill (less than 3 m) had none/minimal carbon loss (Fig. 7). However those samples all originated from the 18-year site, which overall was assessed as having negligible carbon loss (Fig. 6). These results highlight the fact that the decay for the same paper type can vary substantially within the same landfill (e.g. Sydney MSW landfill). The nil to low decay detected for newspapers from Sydney MSW (18 year) indicates a level of inhibition, which is supported by the unusually low pH levels for the material in that site (Table 4). Differences in climate between landfill sites from temperate (i.e. Sydney) to tropical locations (i.e. Cairns) did not influence carbon loss from newspapers (Fig. 6). The lower carbon losses for newspapers in the C&D landfill is likely explained by the absence of more easily digestible organic materials such as food waste (Fig. 6).

The extent of decay of newsprint in landfills has been reported in other studies. Wang et al. (2013) reported greater biodegradation of newsprint that had been buried for 2.5 years in landfill compared to newsprint that had been incubated in the laboratory

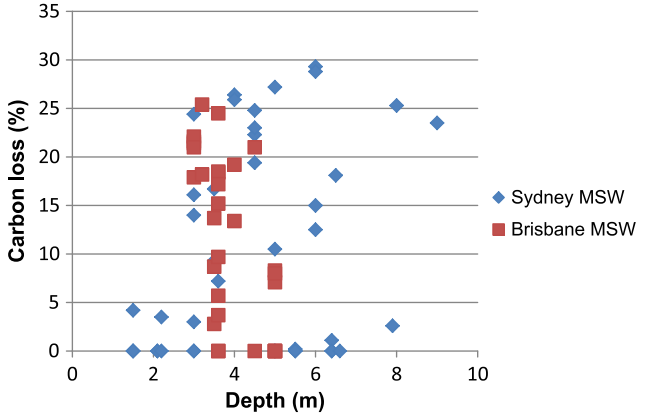

Fig. 7. Carbon loss of newspapers recovered from Sydney MSW and Brisbane MSW according to depth.

under optimal conditions (Eleazer et al., 1997). Wang et al. (2013) hypothesised that the differences in decay may have been due to the higher content of recycled pulp in the newsprint buried

in landfills, with higher holocellulose and lower lignin content. Micales and Skog (1997) estimated that a maximum 15.7% of the carbon contained in newsprint is converted to carbon dioxide and methane, based on published estimates of methane yields in landfills. Baldwin et al. (1998) buried samples of newspaper and filter paper in three landfills representing varying climatic conditions and periodically analysed subsamples over 6 years. Mass loss for newspapers was generally low; only in the wettest site was there a loss of 17% mass after 2 years. Chen et al. (2004) analysed the decay of 15–30 year old excavated newsprint samples, using a range of techniques including infrared spectroscopy and nuclear magnetic resonance (NMR). The lignin concentration of the landfill samples was higher than that of fresh control samples (similar values to those described here), suggesting that some decay of the carbohydrate portion of the samples had taken place. Interestingly, the NMR spectroscopy revealed that newspapers with shorter burial period had decayed to a greater extent than those buried for a longer period, similar to our findings for the Sydney MSW landfill. This suggests that spatial intra-cell variability in environmental conditions in the landfills may be just as important as residence time in stimulating decay activity.

Carbon losses for magazines ranged from 5.5% for Sydney C&D to 58.9% for Cairns MSW (Fig. 6), with magazines from Sydney MSW and Brisbane MSW having similar carbon losses. Carbon loss for telephone directories, with the exception of samples from Cairns MSW, was minimal to minor (Fig. 6). The telephone directory results for Brisbane MSW and Sydney C&D need to be interpreted with caution as they reflect the analysis of only one excavated sample (Fig. 6). As for the newspapers recovered from Sydney MSW (18 years), the magazines and telephone directories recovered from the same site exhibited little to no decay (result not shown), supporting the suggestion that decay was inhibited at that site.

Carbon losses for cardboard ranged from 18.3% for Brisbane MSW to 59.2% for Cairns MSW (Fig. 6). The high carbon losses determined for cardboard need to be interpreted with caution. The excavated cardboard samples included a range of cardboard types (food boxes, waved, corrugated), which may explain the high variability in the results. Cardboard under the FAO definition (FAO, 2004) may fit under five separate categories: packaging and case materials (made from either chemical or mechanical pulp), folding boxboard (mix of mechanical and chemical pulp), wrapping papers (mostly made from chemical pulp) and other papers mainly for packaging (mix of mechanical and chemical pulp). The difficulties in finding suitable controls for the various types of cardboard recovered makes interpretation of results more difficult than for other paper types.

For paperbacks the calculated carbon losses were low (4.9%), comparable to those determined for telephone directories (also made of uncoated mechanical paper) in the Sydney C&D and Brisbane MSW landfills (Fig. 6). It is important to note that the majority of paperback books were recovered from the Sydney MSW (18 years) site, where decay was likely at least partially inhibited by low pH.

Generally papers produced from mostly mechanical pulps (e.g. newspapers and paperback novels) had lower levels of decay than those produced via chemical or partly chemical processes (e.g. magazines and cardboard). This finding is consistent with results from previous laboratory studies (Eleazer et al., 1997; Wang et al., 2015). Although there is agreement in the literature regarding the generally lower levels of decay for papers derived from mechanical pulp, it is important to note that in the manufacture of newsprint, the pulp used may be a mix of mechanical, semi-chemical and chemical pulps. For example, the pulp used in the manufacture of newsprint which would most likely have been used in the production of low-budget magazines, newspapers and paperback books excavated here was likely comprised primarily of thermomechanical pulp (where lignin is retained), with lower proportion of semi-chemical pulp (subjected to a mild chemical treatment where lignin is mostly retained), and a small portion (up to 5%) of chemical pulp, where lignin is largely removed (Ryan, 2001). Differences in the composition of the pulp in newsprint may assist understanding the variability in carbon loss for newspapers excavated from the various landfills (0–22.3%), as higher concentrations of chemical pulp are likely to lead to greater decay.

4. Conclusions and recommendations

4.1. Influence of climate

The generally greater carbon losses – especially for paper – from the "tropical" landfill (Cairns MSW) suggest that climate had a significant impact on anaerobic decay. The effect was more pronounced for paper types other than newspapers, with less mechanical pulp in their composition. In previous work involving sawn wood products from the same landfills as those studied here (Ximenes et al., 2015), it was suggested that climate did not have an impact on anaerobic decay, as judged by decay levels of the same wood species in the different landfills. The greater influence of climate on the decay of paper compared to EWPs as described here, and to solid wood as reported previously, suggests that the altered composition of the wood structure in paper renders it more susceptible to decay when conditions are favourable (i.e. higher average temperature). This finding suggests it would be appropriate to apply different decay factors for papers depending on whether they are buried in landfills in tropical or more temperate climates.

4.2. Effect of landfill type

The generally lower carbon losses for EWP and paper excavated from the C&D landfill confirmed that conditions in C&D landfills are much less suited for decay. This is important, as both sawn and engineered wood products are primarily disposed of in C&D rather than MSW landfills, and the majority of the literature on the anaerobic biodegradability of wood products is based on conditions typical of MSW landfills (both field and laboratory studies). Adoption of separate decay factors for wood and wood products in C&D landfills would be warranted to more accurately represent their behaviour for national greenhouse gas inventories.

4.3. Effect of product type

Our results support the suggestion by others (e.g. Wang et al., 2015) that paper types should be grouped at a minimum in two classes for the purposes of national greenhouse gas inventories: papers produced from mostly mechanical pulps and those produced from mostly chemical pulps, with separate carbon conversion factors provided for each type. The results for the various EWPs suggest that they can be grouped for the purposes of national greenhouse gas inventories.

4.4. Implications for greenhouse gas emission estimation from landfills

The results from this study and those from Wang et al. (2011) are in agreement on the low biodegradability of EWPs such as particleboard and MDF relative to the IPCC default factor (50%) for all organic materials (IPCC, 2014) and the 23% for wood products adopted by the US EPA (US EPA, 2012). Assuming a constant annual rate for EWPs deposited in Australian landfills of approximately

0.5 Mt/yr for the last ten years, and 23% carbon conversion for wood and EWPs (which is adopted by the Australian Government), approximately 2.0 Mt CO_2-e would have been emitted in that period (assuming an oxidation factor of 0.1; methane concentration in the landfill gas of 50%, a methane collection efficiency of 50% and a global warming potential for methane of 25). In contrast, using the mean extent of carbon conversion measured in the laboratory reactor study by Wang et al. (2011) for particleboard, MDF and plywood (1.3%), the estimated emissions for the same mass of EWPs is only 0.11 Mt CO_2-e, or 5.5% of that predicted using the EPA default factor.

In conclusion, determination of carbon losses for EWPs and paper excavated from landfills represents a "reality check" on laboratory-based decomposition studies and is key to understanding the likely actual extent of anaerobic decay of products. In contrast, controlled experiments represent the maximum decay potential. However, caution should be exercised in the interpretation of data from excavation studies, as decay may have taken place prior to disposal in landfill, confounding the emission estimates (especially in the case of EWPs).

Although most countries adopt the IPCC default decay factor for organic materials in landfills (IPCC, 2006), they are encouraged to use country-specific decay factors if available. A follow-up laboratory study that involves the exposure of EWPs and paper products used in Australia to anaerobic decay conditions in controlled bioreactor experiments would be desirable. Such experiments would have a number of benefits, including (1) development of benchmark upper levels of decay for important components of the waste stream; (2) improved understanding of decay drivers under anaerobic conditions; (3) improved understanding of the influence of pulp composition in the decay of paper; and (4) elimination of the potentially confounding issue of aerobic decay prior to burial in landfill.

Acknowledgements

The authors would like to thank personnel at the Brisbane City Council (especially Erik Dekker and Greg McPherson), Eastern Creek Landfill Facility (especially Paul Newcombe and Chris Northey), Cairns Regional Council (especially Steve Wacher) and Brandown Landfill in Western Sydney (especially Nick Renwick) for their assistance and interest in making the landfill sites available for this study. The authors thank Chris Wilson (NSW Department of Industry – Lands), Paul Brooks and David Giles (both previously from NSW Department of Primary Industries) for their analytical chemistry work, and Rebecca Coburn (NSW DPI) for her assistance in the field and in sample handling. Financial support for this work was provided by the CRC for Greenhouse Accounting, the Federal Department of Agriculture, Fisheries and Forestry (DAFF) and Forests and Wood Products Australia (FWPA).

References

ABARES, 2016. Australian forest and wood products statistics: March and June quarters 2016. Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra, November. CC BY 3.0. <http://www.agriculture.gov.au/abares/forestsaustralia/australian-forest-and-wood-products-statistics>.

AOAC, 1995. Official Methods of Analysis of AOAC International, vols. 1 and 2. Arlington, Virginia.

AS/NZS (Australian/New Zealand Standard) 1080.1, 1997. Timber – Methods of Test; Method 1: Moisture Content, Standards Association of Australia.

Bajpai, P., 2012. Chapter 2 – Brief description of the pulp and paper making process. In: Biotechnology for Pulp and Paper Processing, 414 p. ISBN 978-1-4614-1408-7_2.

Baldwin, T.D., Stinson, J., Ham, R.K., 1998. Decomposition of specific materials buried within sanitary landfills. J. Environ. Eng. 124, 1193–1202.

Bogner, J., 1990. Anaerobic burial of refuse in landfills: increased atmospheric methane and implications for increased carbon storage. Ecol. Bull. 42, 98–108.

Brunow, G., Lundquist, K., Gellerstedt, G., 1999. Lignin. In: Sjöström, E., Alén, R. (Eds.), Analytical Methods in Wood Chemistry Pulping and Papermaking. Springer-Verlag, Berlin, Heidelberg, New York, pp. 77–124.

Bureau of Meteorology, Australia, 2014. <http://www.bom.gov.au/climate/averages/tables/cw_066124.shtml>.

Chen, L., Nanny, M.A., Knappe, D.R.U., Wagner, T.B., Ratasuk, N., 2004. Chemical characterization and sorption capacity measurements of degraded newsprint from a landfill. Environ. Sci. Technol. 38 (13), 3542.

Colberg, P., 1988. Anaerobic microbial degradation of cellulose, lignin, oligolignols and monoaromatic lignin derivatives. In: Zehnder, A.J.B. (Ed.), Biology of Anaerobic Microorganisms, vol. 28. Wiley-Interscience, New York, pp. 886–889.

De la Cruz, F.B., Yelle, D.J., Gracz, H.S., Barlaz, M.A., 2014. Chemical changes during anaerobic decomposition of hardwood, softwood, and old newsprint under mesophilic and thermophilic conditions. J. Agric. Food Chem. 62 (27), 6362–6374.

Department of Environment, 2014. National Inventory Report 2012 Volume 3, Commonwealth of Australia 2014. http://www.environment.gov.au/system/files/resources/6b894230-f15f-4a69-a50c-5577fecc8bc2/files/national-inventory-report-2012-vol3.pdf.

Department of the Environment, Water, Heritage and the Arts, 2010. A National Waste Policy: Managing Waste to 2020. 59 p.

Eleazer, W.E., Odle, W.S., Wang, Y.S., Barlaz, M.A., 1997. Biodegradability of municipal solid waste components in laboratory-scale landfills. Environ. Sci. Techol. 31, 911–917.

FAO (Food and Agriculture Organization), 2004. Timber Bulletin: Forest Products Statistics 1997–2001 United Nations Economic Commission for Europe, United Nations Publications, 28May, 2004 – Nature – 146 pages.

FAO (2011). Highlights on wood pulp and other fibre furnish: 1999–2009 (Wood pulp, other fibre pulp and recovered paper). Report prepared by Mr Jukka Tissari. <http://faostat.fao.org/Portals/_Faostat/documents/pdf/Wood%20pulp%20and%20other%20fibre%20furnish.pdf>.

Fengel, D., Wegener, G., 1984. Wood – Chemistry Ultrastructure Reactions. Walter de Gruyter, Berlin, New York, p. 153.

Ham, R.K., Frischel, P.R., Norman, M.R., 1993. Refuse decay at a large landfill. In: Proceedings of the fourth International Landfill Symposium, Sardinia, Italy, pp. 1046–1054.

Hedges, J.I., Cowie, G.L., Ertel, J.R., Barbour, R.J., Hatcher, P.G., 1985. Degradation of carbohydrates and lignins in buried woods. Geochim Cosmochim Acta 49, 701–711.

Intergovernmental Panel on Climate Change (IPCC), 2006. Waste. In: Eggleston, S., Buendia, L., Miwa, K., Ngara, T., Tanabe K., (Eds.), Guidelines for National Greenhouse Gas Inventories, vol. 5. Institute for Global Environmental Strategies, Hayama, Japan, pp. 3.13–3.15. Available online: <http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html>.

Intergovernmental Panel on Climate Change (IPCC), 2014. Section 2.8. Harvested wood products. In: Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., Troxler, T.G. (Eds.), 2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol Hiraishi. IPCC, Switzerland.

Kinman, R., Rickabaugh, J., Berg, G., Nutini, D., Rathje, W., 1990. Analysis of 20-year old refuse from the Mallard North landfill in Chicago, Illinois. In: Proceedings from the 44th Purdue Industrial Waste Conference, pp. 527–536.

Kipphan, H., 2001. Handbook of Print Media: Technologies and Production Methods. Springer Science & Business Media.

Micales, J.A., Skog, K.E., 1997. The decay of forest products in landfill. Int. Biodet. Biodegr. 39 (2), 145–159.

NREL (National Renewable Energy Laboratory), 2008. Determination of Ash in Biomass Laboratory Analytical Procedure (LAP) Issue Date: 7/17/2005A. Sluiter, B. Hames, R. Ruiz, C. Scarlata, J. Sluiter, and D. Templeton Technical Report NREL/TP-510-42622. January 2008.

Rathje, W., Murphy, C., 1992. Rubbish: The archaelogy of garbage. Harper Collins, New York, p. 250.

Ryan, R. 2001. Boyer's new buyer finds value in mill. Pulp and Paper International, Online addition. <http://www.risiinfo.com/db_area/archive/ppi_mag/2001/0108/ppi5.htm>.

Sjöström, E., Westermark, U., 1999. Chemical composition of wood and pulps: basic constituents and their distribution. In: Prof. Dr. Eero Sjöström, Prof. Dr. Raimo Alén (Eds.), Analytical Methods in Wood Chemistry, Pulping, and Papermaking. Springer Series in Wood Science.

Stark, N.M., Cai, Z., Carll, C., 2010. Chapter 11 – Wood-based composite materials: panel products, glued-laminated timber, structural composite lumber, and wood–nonwood composite materials. In: Ross, Robert J. (Ed.), Wood Handbook, Wood as an Engineering Material. General Technical Report FPL–GTR–190. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. 508 p.

Sustainability Victoria, 2014. Market summary – recycled timber. Fact sheet produced for Sustainability Victoria by NetBalance. September 2014, 5 p. Accessed on January 2017 at: <http://www.sustainability.vic.gov.au/~/media/resources/documents/publications%20and%20research/research/market%20analysis/market%20analysis%20timber%20sept%202014%20pdf.pdf>.

US EPA. 2012 <http://epa.gov/epawaste/conserve/tools/warm/pdfs/Wood_Products.pdf>.

Walsh, D.C., LaFleur, R.G., 1995. Landfills in New York City: 1844–1994. Ground Water 33, 556–560.

Ximenes, F.A., Gardner, W.D., Cowie, A., 2008. The decay of wood products in landfills in Sydney, Australia. Waste Manage. 28, 2344–2354.

Ximenes, F., Björdal, C., Cowie, A., Barlaz, M., 2015. The decay of wood in landfills in contrasting climates in Australia. Waste Manage. 41, 101–110.
Xing, C., Deng, J., Zhang, S.Y., Riedl, B., Cloutier, A., 2006. UF resin efficiency of MDF as affected by resin content loss, coverage level and pre-cure. Holz als Roh- und Werkstoff 64 (3), 221–226.
Wang, X., Padgett, J.M., De la Cruz, F.B., Barlaz, M.A., 2011. Wood biodegradation in laboratory scale landfills. Environ. Sci. Technol. 45, 6864–6871.
Wang, X., Padgett, J.M., Powell, J.S., Barlaz, M.A., 2013. Decay of forest products buried in landfills. Waste Manage. 33, 2267–22276.
Wang, X., De la Cruz, F.B., Ximenes, F., Barlaz, M.A., 2015. Decomposition and carbon storage of selected paper products in laboratory-scale landfills. Sci Total Environ. 532, 70–79.